THE SPIN HISTORY OF PROTOSTARS: DISK LOCKING, REVISITED

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RESUMEN

ABSTRACT

In this talk, we take a new look at the theory of disk locking, which assumes that an accreting protostar rids itself of accreted angular momentum through a magnetic coupling with the accretion disk. We consider that differential rotation between the star and disk twists the field lines. For large enough twist, the magnetic field lines connecting the star and disk open and disconnect. This significantly reduces the spin-down torque on the star by the disk, and so we find that disk-locking theory predicts spin periods that are much too short to account for typical observed systems.

Key Words: **ACCRETION, ACCRETION DISCS — MHD — STARS: FORMATION — STARS: MAGNETIC FIELDS — STARS: PRE-MAIN-SEQUENCE — STARS: ROTATION**

1. INTRODUCTION

The collapse of a molecular cloud naturally leads to a phase consisting of a central protostar surrounded by a centrifugally supported accretion disk (for a review, see Bodenheimer 1995). Disk winds, MRI turbulence, and/or viscous processes remove angular momentum from the disk and results in the accretion of material with high specific angular momentum onto the star. For typical parameters for accreting protostars (CTTS's), the accretion alone will spin the star up to near breakup speed in less than $\sim 10^5$ years, assuming the star hadn't already formed at near breakup speed. Since the accretion lifetime is often greater than 10^6 yr, the stars must rid themselves of this excess angular momentum. Further, it has been generally accepted that accreting protostars spin more *slowly* than their non-accreting counterparts (e.g., Bouvier et al. 1993). The general explanation is that the presence of an accretion disk somehow regulates the stellar spin, and then after the disk is dispersed, the star spins up as it contracts toward the main sequence.

Königl (1991) applied the neutron star accretion model of Ghosh & Lamb (1979) to accreting protostars and showed that a "disk-locking" (DL) mechanism could explain the coincidence of accretion and slow rotation, in those systems. According to DL theory, magnetic field lines connect the star to the disk (acting as "lever arms") and carry torques that oppose and balance the angular momentum deposited by accretion. CTTS's are now known to posses kilogauss-strength fields (e.g., Johns-Krull, Valenti, & Koresko 1999), and the general DL model has been invoked by many authors.

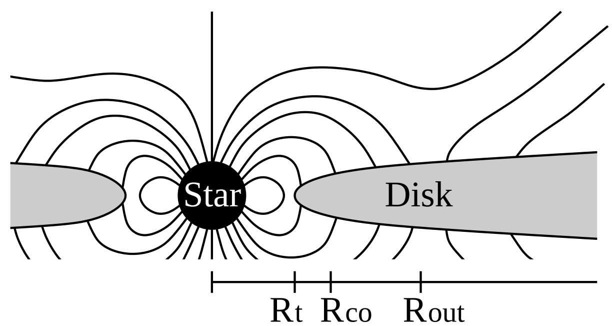

Fig. 1. Magnetic star-disk interaction. (from Matt & Pudritz 2004)

Recent observations of CTTS's in Orion by Stassun et al. (1999), however, show no correlation between observed rotation periods and accretion diagnostics, calling the standard DL scenario into question. Furthermore, the magnetic fields of CTTS's, while strong, are disordered (Safier 1998; Johns-Krull et al. 1999), which reduces the effectiveness of magnetic torques required for DL. These developments prompted us to revisit the general theory of DL. In particular, the connectivity between the star and disk is an important issue. Much recent work has shown that the magnetic connection between the star and disk is severed when the magnetic field is highly twisted. Here, we show that the resulting spin-down torque is significantly reduced, and the DL model cannot account for accreting stars that spin slowly (e.g., ∼10% of breakup speed).

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2. THE "STANDARD" DL MODEL

To begin, we first formulate a basic model that is representative of the general DL picture discussed by many authors. We follow the work of Armitage & Clarke (1996, hereafter AC96). The general theory assumes the central star contains an axis-aligned dipolar magnetic field. A dipole is required because the field strength falls off as slowly as nature allows (r^{-3}), and any higher order multipole falls off so quickly that torques become negligible. The dipole field is anchored in the surface of the star and also connects to the accretion disk, which is assumed to always be in Keplerian rotation. The disk accretion rate $\dot{M}_\mathrm{a}$ is constant in time and at all radii in the disk. Figure 1 illustrates the basic idea and identifies the location where the disk is truncated (R_t), the outermost radius where the closed stellar field is connected to the disk (R_out), and the corotation radius (R_co), where the Keplerian angular rotation rate equals that of the star. The usual assumption is that $R_\mathrm{out} \gg R_\mathrm{co}$ (AC96 used $R_\mathrm{out} \to \infty$).

The magnetic torque on the star from field lines threading some range of radii in the disk midplane is given by

$$\tau_\mathrm{m} = \int_{R_\mathrm{t}}^{R_\mathrm{out}} \gamma \frac{\mu^2}{r^4} \delta r \qquad \text{where} \qquad \gamma \equiv \frac{B_\phi}{B_z} \tag{1}$$

(e.g., AC96) where μ is the dipole moment, and γ is the "twist" of the magnetic field. So the torque depends not only on the strength of the field but, more importantly, on how much it is twisted. The more it is twisted (larger γ), the stronger the torques.

The field twist is generated by the differential rotation between the star and disk. As the field is twisted, it resists the twisting (hence the torques) and slips backwards through the disk. The larger the γ, the faster the slipping. When it can slip backward at the same rate as the differential rotation rate between the star and disk, a steady-state for γ is achieved. The speed of slipping field lines is given by $v_\mathrm{d} = \beta v_\mathrm{kep} \gamma$, where β is a constant scale factor by which v_d compares to the Keplerian speed, v_kep (AC96 use $\beta = 1$). Thus, the steady-state configuration of $\gamma(r)$ is given by $\gamma = \beta^{-1}[(r/R_\mathrm{co})^{3/2} - 1]$, and so the torque in equation 1 can be calculated. The value of β is unknown. Standard α-disk physics (Shakura & Sunyaev 1973) gives an upper limit of $\beta \leq 1$ and a likely value of a few orders of magnitude lower. We consider a value of $\beta = 10^{-2}$ as reasonable, but given the uncertainties, we keep β as a free parameter in our analysis. At first, we will use $\beta = 1$ (which gives the solution of AC96), but we consider other values in the next section.

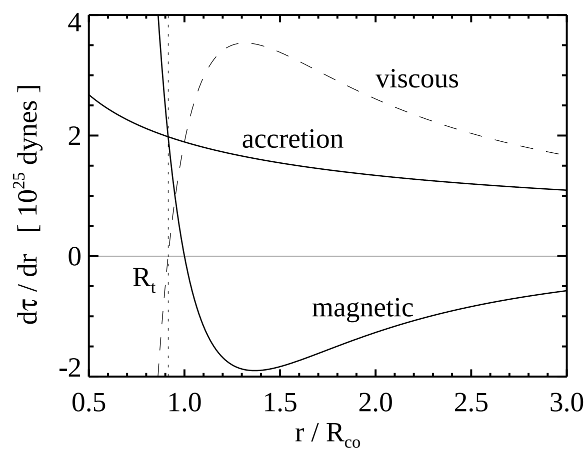

Fig. 2. Differential torques in the disk midplane for a system with $\beta = 1$, $\dot{M}_\mathrm{a} = 5 \times 10^{-8} M_\odot \mathrm{yr}^{-1}$, $M_* = M_\odot$, $R_* = 3R_\odot$, $B_* = 10^3$ G, and a stellar spin period of 5.7 days (so $R_\mathrm{co} = 4.5R_*$). (from Matt & Pudritz 2004)

Figure 2 shows the differential torques (per δr) as a function of radius (normalized to R_co) in the disk midplane, for a system with the parameters listed in the figure caption. The line labelled "accretion" represents torque that is required to supply the steady-state $\dot{M}_\mathrm{a}$. The line labeled "magnetic" shows the differential torque (from eq. 1) from the stellar field threading the disk. Inside R_co, this torque acts to spin the star up. It decreases rapidly away from the star as the dipole field becomes weaker. It is zero at R_co because the differential rotation (and thus γ) is zero there. Outside R_co it becomes stronger (though now spinning down the star) as γ increases, but it eventually becomes weaker again because the decrease in the dipole field strength decreases faster than the increase of the γ. In order to satisfy the steady-state condition, the disk must restructure itself so that the sum of the magnetic and internal disk differential torques must equal the accretion differential torque at all radii. The dashed line labelled "viscous" in Figure 2 shows the required internal disk torque.

The disk will be truncated near where the accretion and magnetic differential torques are equal (and where viscous torque = 0). From that point (R_t) inward, all of the specific angular momentum of the disk material will end up on the star. So, to calculate the net torque on the star from the accretion of disk material, τ_a, one integrates the differential accretion torque (shown in Fig. 2) from R_t to the surface of the star. The net magnetic torque, τ_m, is

obtained by integrating equation 1 from R_t to R_{out} (which is thus far assumed to be ∞).

For any given values of M_*, R_*, B_*, $\dot{M}_a$, and the stellar rotation period, this "standard" theory gives the net torque on the star. The system is stable in that, for fast rotation, the net torque spins the star down, and for slow rotation, the star spins up. Also, for typical CTTS parameters, the torques spin the star up or down in $\sim 10^5$ yr, so one expects that most systems will exist in a spin equilibrium state where the net torque on the star is zero. The "standard" DL model thus predicts the spin period in the equilibrium state, T_{eq}, at which the system is "disk locked." Figure 2 is shown in its equilibrium spin state ($T_{eq} = 5.7$ d).

Models such as this have had success at explaining the spin rates of slow rotators. For example, the well-studied CTTS, BP Tau has $\dot{M}_a = 3 \times 10^{-8} M_\odot$ yr^{-1}, $R_* = 2R_\odot$, and $M_* = 0.5M_\odot$ (Gullbring et al. 1998). Using the mean field strength of 2 kG found by Johns-Krull et al. (1999), our "standard" DL theory predicts $T_{eq} = 7.5$ d (corresponding to 6% of breakup speed)—remarkably similar to the observed value of 7.6 d (Vrba et al. 1986). Thus the DL theory *seems* to work, but there's at least one major problem. Namely, we assumed that the star and disk were connected to $R_{out} \to \infty$. At large radii, the field will be highly twisted, and there is a physical limit to that twist, which we have so far ignored. In the next section, we consider the effect on the DL model of an upper limit to the magnetic twist.

3. EFFECT OF LIMITED TWIST

Twisted magnetic fields that connect the star to the disk exert torques between the two. The larger the region in the disk that is magnetically connected to the star, the larger is the total magnetic torque. So the actual location of R_{out} is important, since it delimits the connected region (i.e., it determines the integration range in eq. 1). Many recent studies (see Uzdensky, Königl, & Litwin 2002, and references therein) have shown that dipole magnetic field lines connected to a rotating disk open up, when twisted past a critical value of $\gamma = \gamma_c \approx 1$. This is unavoidable and occurs because the magnetic pressure associated with the azimuthal component of magnetic field pushes out against the poloidal field lines. These open field lines (see, e.g., the field lines outside R_{out} in Fig. 1) cannot convey torques between star and disk.

Since the steady-state value of γ increases as $r^{3/2}$ away from R_{co} (see §2), it inevitably reaches the critical value, which we take as $\gamma_c = 1$. As an approximation, we assume that the star is connected

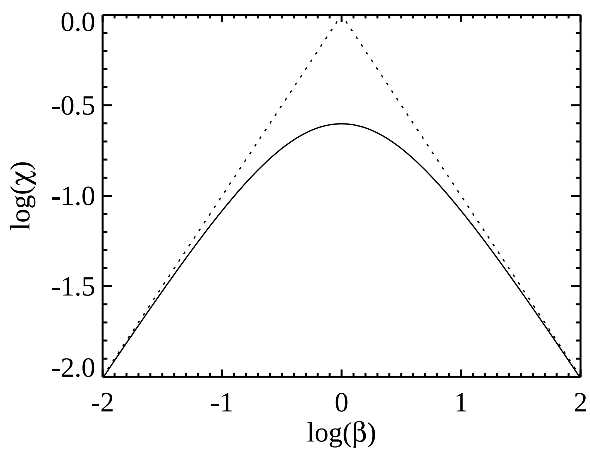

Fig. 3. Logarithm of the net magnetic torque as a function of $\log(\beta)$. The torque (denoted χ, see text) is normalized to the AC96 value, so that the value of $\chi = 1$ is the torque from the "standard" DL theory, and the solid line shows the effect of limited magnetic twist. For reference, the dotted lines show $\chi = \beta$ and $\chi = \beta^{-1}$. (from Matt & Pudritz 2004)

as before to the disk, but that the extent of connected region is now limited to the region where $\gamma \leq \gamma_c$. The outermost location of this region is $R_{out} = (1 + \beta\gamma_c)^{2/3} R_{co}$, beyond which, we assume the star is disconnected from the disk, and so the differential torque is zero. Since the size of the connected region is smaller than for the "standard" model, the net magnetic torque is less.

Figure 3 illustrates how the magnetic torque is altered by the opening of field lines, as a function of the parameter β. Shown is the value of the net magnetic torque (denoted χ), renormalized so that the torque predicted by the "standard" DL theory of the previous section ($\beta = 1$ and $R_{out} = \infty$) gives a value of $\chi = 1$. The normalization allows Figure 3 to be valid for any given values of $\dot{M}_a$, M_*, μ, and the stellar spin period. It is evident that the magnetic torque will always (for any β) be significantly less than predicted by the "standard" theory. The dependence of χ on β can be understood as a competition between two different effects: One is that R_{out} decreases for decreasing β, reducing the integration range of equation 1; the other is that the steady-state γ decreases for increasing β, reducing the differential torque at each radius. For the critical value of $\beta = 1$, these two effects conspire to give a maximal value of τ_m that is four times less than predicted by the "standard" DL theory of section 2 (for any given values of $\dot{M}_a$, M_*, Ω_*, and μ). So by using $\beta = 1$ above, we have considered the "best pos-

sible case" for DL theory, since $\tau_{\rm m}$ is less for all other values of β. A reduced magnetic torque, means that the star must spin faster before it is in equilibrium. A faster spin reduces $R_{\rm co}$, so the torques come from closer to the star where the dipole field is stronger, making up for the decreased integration range.

We can now revisit our example case of BP Tau. Using the "updated" DL theory ($\gamma_{\rm c} = 1$), the "best case" value of $\beta = 1$ predicts $T_{\rm eq} = 4.1$ d. For $\beta = 0.1$ (or $\beta = 10$), $T_{\rm eq} = 2.5$ d. The time to spin up from 7.6 d to 4.1 d (or even to 2.5 d) is 1×10^5 yr, which is significantly shorter than BP Tau's age of 6×10^5 yr (Gullbring et al. 1998). Therefore, BP Tau has either gone through a recent change in (e.g.) $\dot{M}_{\rm a}$, so that it is not currently in the equilibrium state, or the model is incomplete. In order for BP Tau to currently be in an equilibrium spin state, there must be significant spin-down torques on the star other than the torques along field lines connecting it to the disk. As an aside, we note that we have thus far used the mean stellar magnetic field strength of 2 kG found by Johns-Krull et al. (1999), though this is not the true strength of the *dipole* field. If instead we use the 3σ upper limit to the dipole field strength of 200 G (Johns-Krull et al. 1999), even the "standard" theory predicts $T_{\rm eq} = 1.0$ d.

4. SUMMARY OF PROBLEMS WITH DL

The disk-locking scenario has recently been called into question by observations, as well as by theoretical considerations. In particular, there are four, completely independent issues:

1. Stassun et al. (1999) found no correlation between accretion parameters and spin rates of TTS in Orion.

2. CTTS's apparently do not have strong *dipole* fields (e.g., Safier 1998; Johns-Krull et al. 1999).

3. Stellar winds are expected to open field lines that would otherwise connect to the disk (Safier 1998). A disk wind would have a similar effect.

4. Finally, a large portion of the magnetic field connecting the star to the disk will open up, due to the differential rotation between the two (e.g., Uzdensky et al. 2002). We have shown that the resulting spin-down torque on the star by the disk is less (by at least a factor of four and possibly by orders of magnitude) than calculated by previous authors. The predicted equilibrium spin rate is therefore much faster.

So the DL scenario does not explain the angular momentum loss of the so called slow rotators—the group originally targeted by DL theory.

We conclude that, in order for accreting protostars to spin as slowly as 10% of breakup speed, there must be spin-down torques acting on the star other than those carried by magnetic field lines connecting the star to the disk. The presence of open stellar field lines naturally leads to the possibility that excess angular momentum is carried by a stellar wind along those open lines. We plan to investigate this possibility in the near future.

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